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In a recent paper [D. Chavan *et al.*, Rev. Sci. Instrum. **81**, 123702 (2010)] we have demonstrated that ferrule-top cantilevers, obtained by carving the end of a ferruled fiber, can be used for contact mode atomic force microscopy in ambient conditions. Here we show that those probes can provide tapping mode images at both room and cryogenic temperatures (12 K). © *2011 American Institute of Physics*. [doi:10.1063/1.3579496]

In 2006, one of us (D.I.) and his collaborators introduced a miniaturized optomechanical transducers for remote sensing: the fiber-top cantilever.[1] In a fiber-top probe, the cleaved end of an optical fiber is carved in the form of a cantilever, whose mechanical deflection is then determined by coupling light from the opposite side of the fiber. Fiber-top cantilevers have been proven to provide a new platform for several applications, including gas sensing,[2] refractive index measurements,[3] and atomic force microscopy.[4] Unfortunately, fiber-top cantilevers are currently fabricated by means of a time consuming process that does not adapt well to series production (namely, focused ion beam milling[5]). This problem was solved at the beginning of 2010 by introducing a larger (but still compact and monolithic) device that retains the advantages of fiber-top technology without the burden of the fabrication costs: the ferrule-top cantilever.[6,7] In a ferrule-top device, the cantilever is carved out of a ferruled optical fiber. Because the dimensions of a ferrule are much large than those of a fiber, ferrule-top cantilevers can be fabricated with a series of steps that adapt better to cost effective series production. In a previous paper,[8] we demonstrated that a ferrule-top probe, equipped with a sharp conical tip on its free hanging end, can be successfully used for atomic force microscope imaging in air and liquids. The study, which was conducted with a custom-made scanner, was limited to contact mode. In this note, we show that a ferrule-top cantilever, now mounted on a commercial atomic force microscope, can provide tapping mode images at both room and cryogenic temperature (12 K).

The ferrule-top cantilever used in this experiment was fabricated following a similar procedure as that described in Ref. 8 (see Figs 1 and 2). The building block is a 3 mm × 3 mm × 7 mm double-bore ferrule made out of borosilicate glass, which is carved in the form of a cantilever via laser ablation. The two bore holes, with a diameter of 127 and 50 μm, are symmetrically positioned with respect to the central axis of the ferrule, with a center-to-center separation of 250 μm. The smaller bore hosts a highly doped optical fiber, on top of which is a sharp conical tip obtained via differential wet etching.[9,10] This fiber, which forms the tip for scanning, is glued into the bore before carving the undercut that frees the cantilever. The larger bore hosts a standard single mode optical fiber, which is glued into the ferrule only after the carving process is completed. The cleaved end of this fiber is kept well below the cantilever itself, and the hole left in the cantilever just above the fiber is filled with a droplet of UV curable epoxy. At the end of the process, the probe is mounted on a metal deposition system, where it is coated with a thin Cr + Au layer. We refer the reader to Ref. 8 for a discussion of the resolution and capabilities of this fabrication method. Here we only want to stress that the cantilever used for the measurements presented in this note was 1600 μm long, 210 μm wide, and 30 μm thick with an expected spring constant of 20 N/m and a measured resonance frequency of 9.8 kHz.

The ferrule-top probe was mounted on an AttoAFM Ixs atomic force microscope (Attocube Systems AG; for details, see Ref. 11). This instrument, which can operate down to a few millidegrees Kelvin , usually relies on standard cantilevers, which are held just below the cleaved facet of an

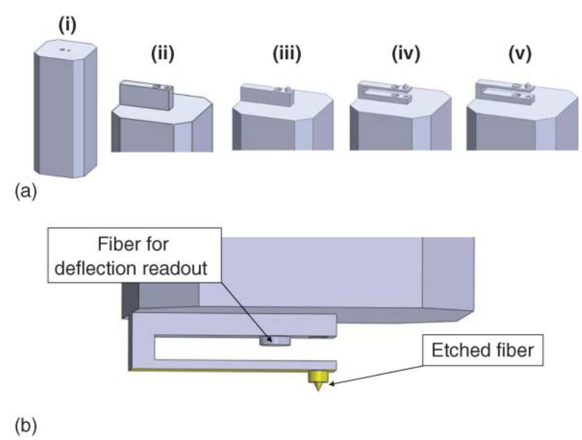

FIG. 1. (Color online) (a) Illustration of the fabrication steps followed for the production of tipped ferrule-top cantilevers (not to scale): (i) the ferrule; (ii) fabrication of the ridge; (iii) assembly of the etched tipped fiber; (iv) fabrication of the undercut; (v) assembly of the readout fiber and filling of the remaining hole. The probe is eventually coated with a thin metallic layer (not illustrated). (b) Schematic view of a ferrule-top probe.

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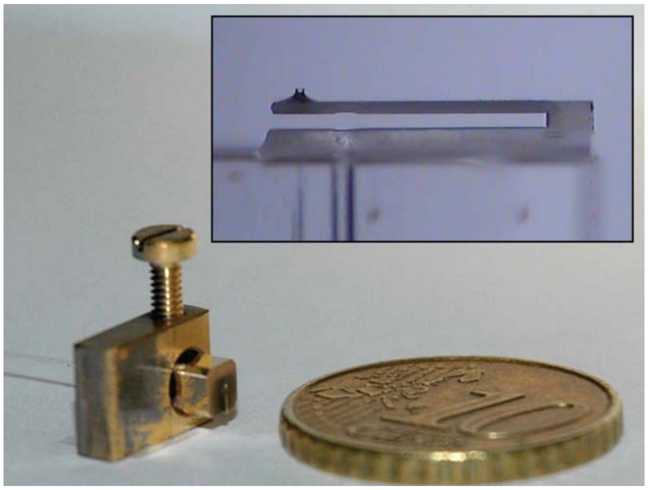

FIG. 2. (Color online) Picture of a ferrule-top cantilever close to a 10 Euro-cents coin. Inset: Microscope image of a ferrule-top cantilever.

optical fiber. Light from a laser coupled into the opposite end of the fiber allows interferometric detection of cantilever's deflections.[12] The wavelength of the laser (Pro8000 WDM-source, 1543 nm) can be adjusted to tune the optical cavity to quadrature. This readout system is very similar to the one used to measure cantilever's deflections in ferrule-top devices (see Refs. 6–8). One can thus plug thestandard single mode optical fiber of the ferrule-top cantilever to the AttoAFM's readout system, mount the ferrule-top probe on the head of the instrument and set the instrument to work without any change of setup, electronics, computer program, or data analysis technique. The monolithic structure of our probe, which removes the burden of the fiber-to-cantilever alignment, simplifies the mechanical assembly of the cantilever, minimizes drifts, and eliminates the three motors that would be needed to align the fiber with the cantilever when standard probes are used.

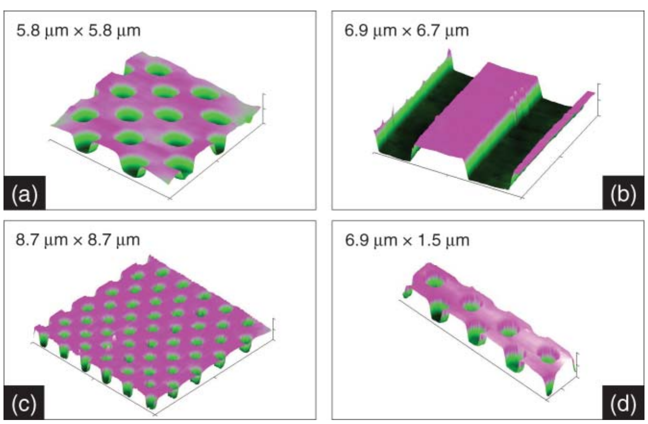

FIG. 3. (Color online) (a) Atomic force microscope image of a 20 nm high calibration grating obtained with the ferrule-top cantilever operating in contact mode at room temperature. (b) Atomic force microscope image of a 20 nm high calibration grating obtained with the ferrule-top cantilever operating in tapping mode at room temperature. (c) Atomic force microscope image of a 20 nm high calibration grating obtained with the ferrule-top cantilever operating in contact mode at 12 K. (d) Atomic force microscope image of a 20 nm high calibration grating obtained with the ferrule-top cantilever operating in tapping mode at 12 K.

In Fig. 3, we report four images of a 20 nm high calibration sample (Anfatec AG, UMG01) obtained under different working conditions. The 200 × 200 pixels image reported in Fig. 3(a) and the 150 × 145 pixels image reported in Fig. 3(b) were obtained in air at room temperature using contact mode and tapping mode, respectively. The third 150 × 150 pixel image [inset (c)] was obtained in lowpressure exchange gas atmosphere (5 torr) at 12 K using contact mode. The fourth image [inset (d)], which, because of the tendency of the substrate to accumulate electrostatic charges, is limited to 150 × 33 pixels, was obtained in vacuum at 12 K using tapping mode. These measurements prove that ferrule-top probes can provide contact mode and tapping mode images of the same quality of those obtained with standard cantilevers, both at room and cryogenic temperatures.

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[11] http://www.attocube.com/nanoSCOPYxs/afmIxs.htm.
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